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Exponential sine sweeps for the autonomous estimation of nonlinearities and errors assessment by bootstrap Application to thin vibrating structures

Marc Rébillat¹, Kerem Ege², Maxime Gallo², Jérôme Antoni²

A linear behavior in vibroacoustics ?

- Geometrically nonlinear vibrations of plates, shells:

when the amplitude of the transverse displacement w
exceeds the plate/shell thickness h



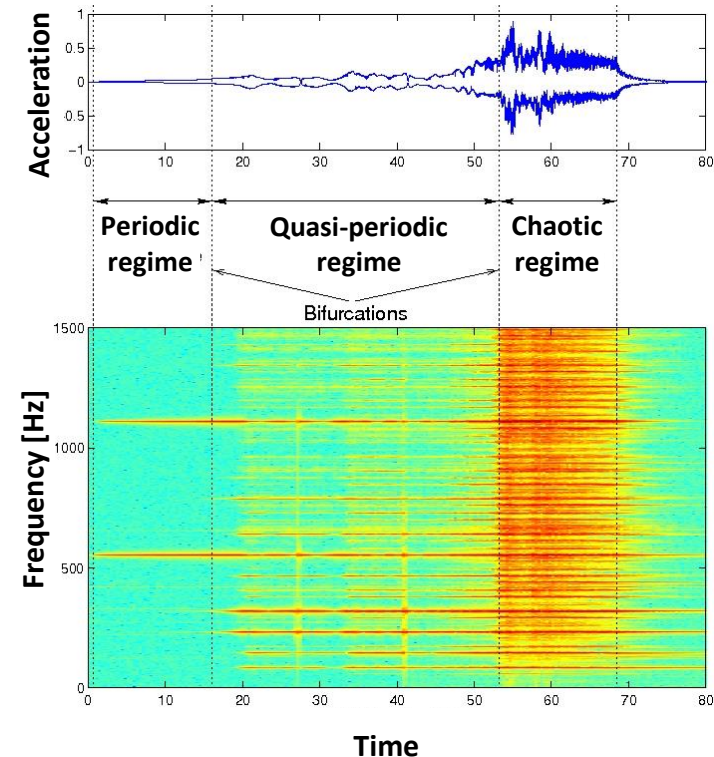
→ *jump phenomenon, hysteresis,
internal resonance*

- Boundary conditions, joints, contacts...



Example : Gong

Cyril Touzé, Olivier Thomas

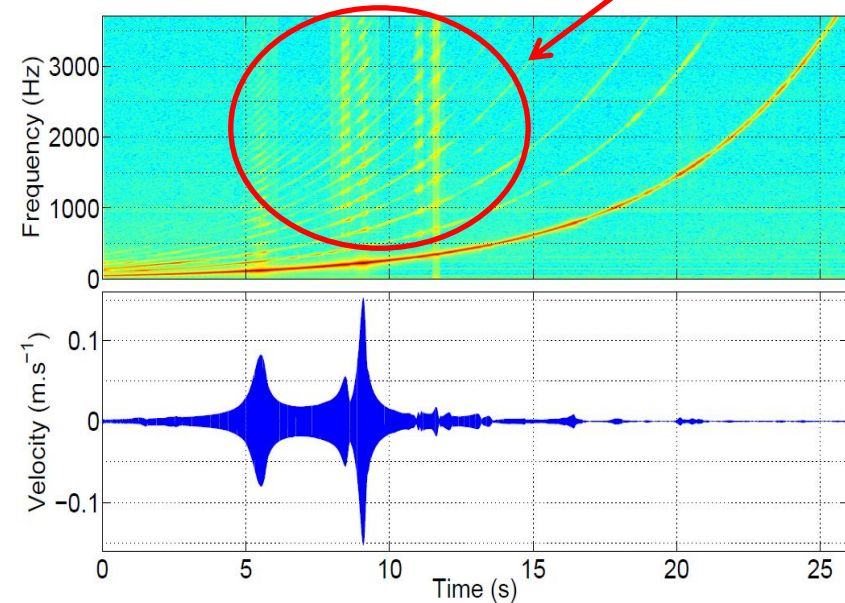


A linear vibroacoustic measurement ?

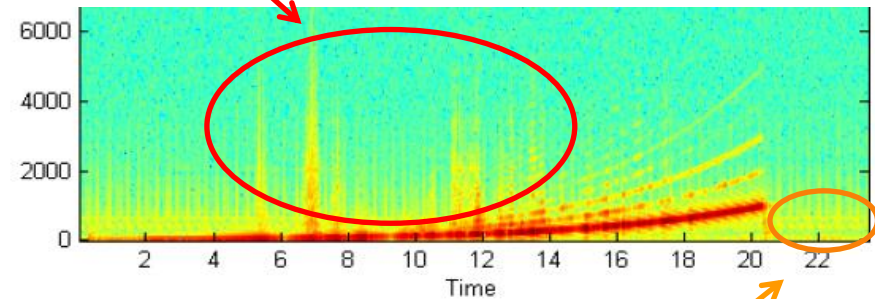
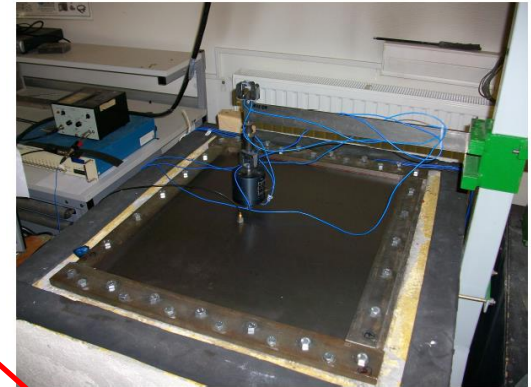
Acoustical excitation



How to extract the linear/nonlinear parts of a typical vibroacoustic measurement ?



Vibrational excitation

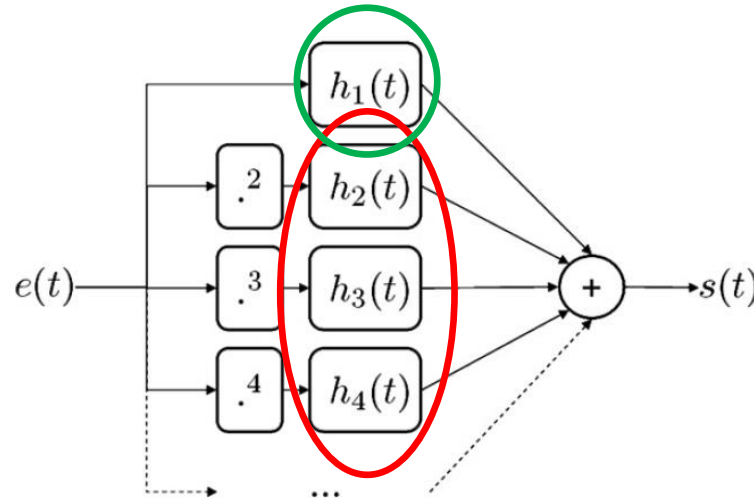


How to estimate the effects of experimental noise ?

- Estimation of Parallel Hammerstein models
 - Theory
 - Application to a vibrating plate
 - Separation of the intrinsic nonlinear contributions
- Improvements of the method (sweep repetition)
 - Theory
 - Noise estimation by synchronous averaging
 - Uncertainty estimation by bootstrap
 - Autonomous kernel order estimation
- Conclusion and perspectives

Parallel Hammerstein models estimation

⇒ Slightly nonlinear system modeled as **parallel Hammerstein models**

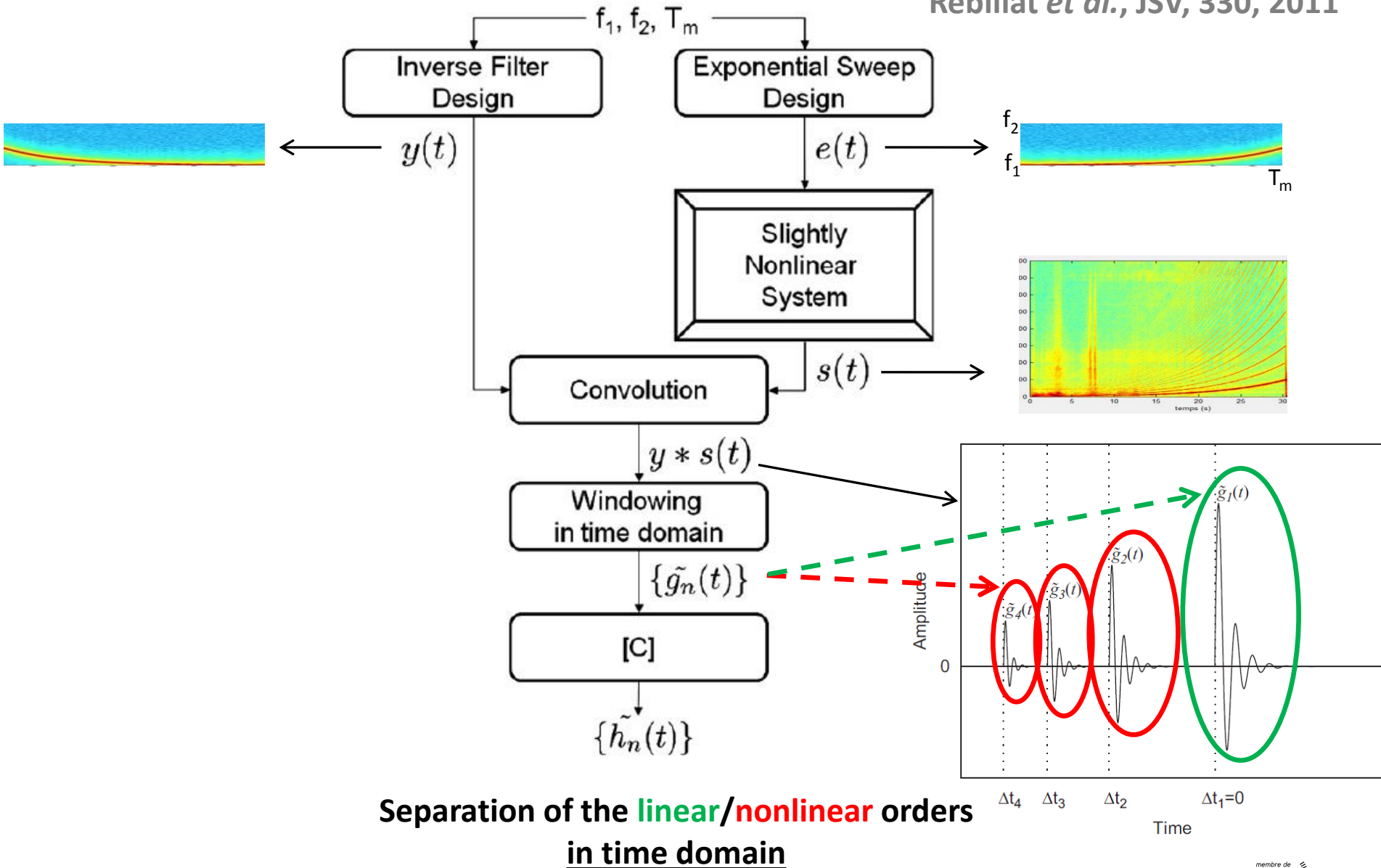


⇒ Kernels easily estimated using **exponential sine sweeps**
(see [Farina, AES, 2000], [Rébillat, JSV, 2011] or [Novak, IEEE Instrumentation, 2011] for example)

→ Separation of the **linear/nonlinear** orders

Parallel Hammerstein models estimation

Rébillat *et al.*, JSV, 330, 2011

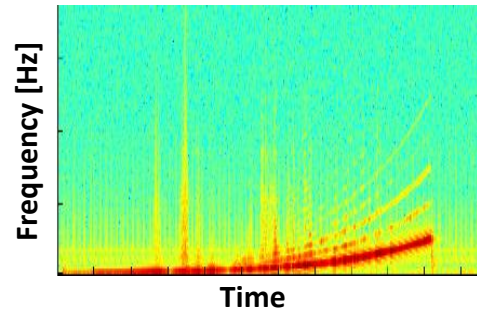


Separation of the **linear/nonlinear** orders
in time domain

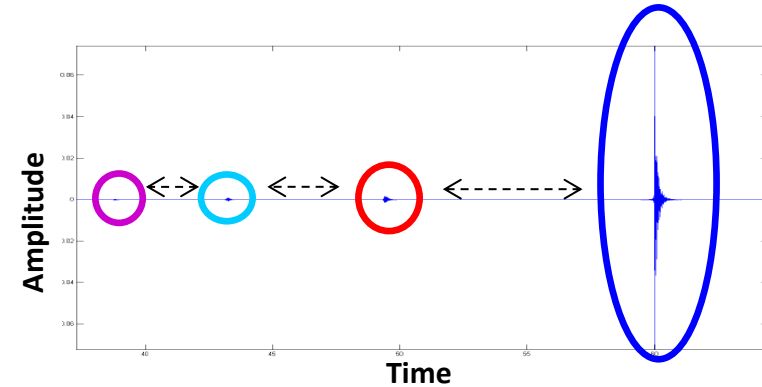
Application to a vibrating plate

- Clamped Steel plate (1mm)
- Shaker + Accelerometer

One sweep of **20 seconds**
[20Hz-1kHz]

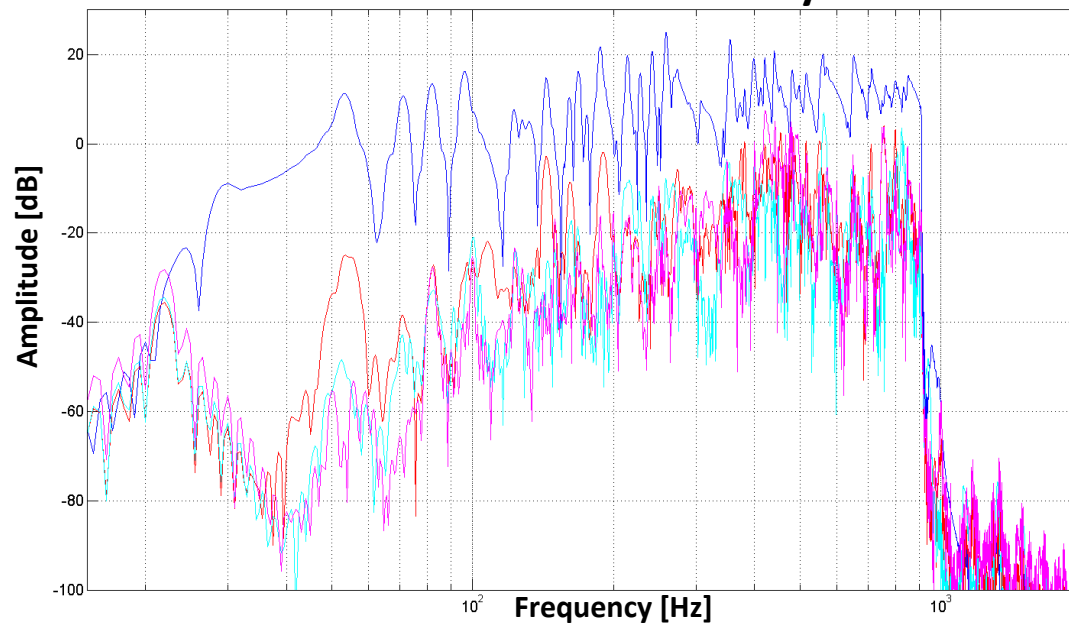


After deconvolution:



Importance of the **length of the sweep** for
time domain separation

Identified Kernels of the system

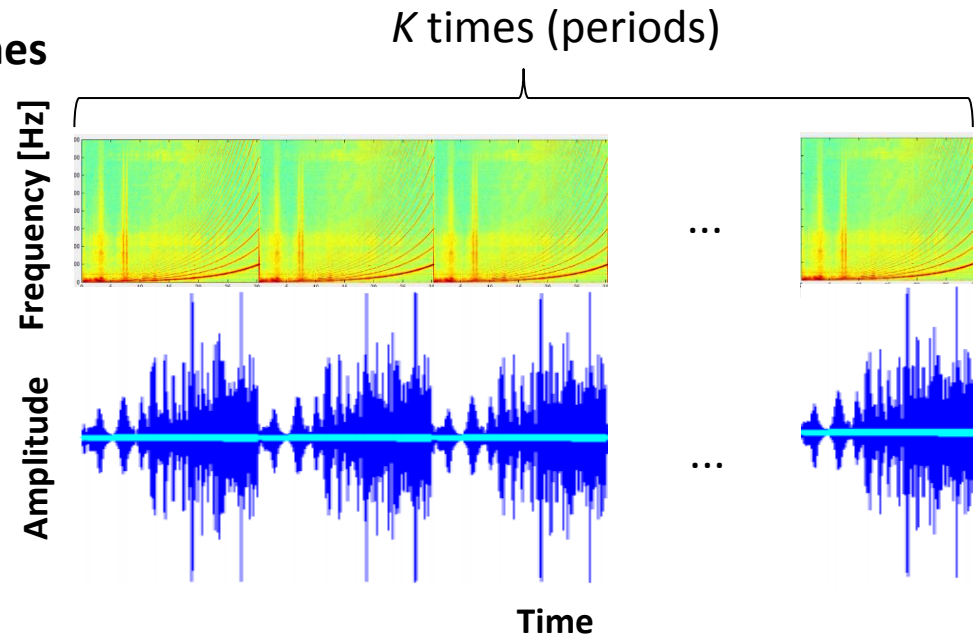


- Kernel h_1 (linear part)
- Kernel h_2
- Kernel h_3
- Kernel h_4

Improvement of the method: Sweep repetition & Noise estimation

- Measured signal = system response + experimental noise $x(t) = s(t) + n(t)$

- Repetition of the same sweep K times



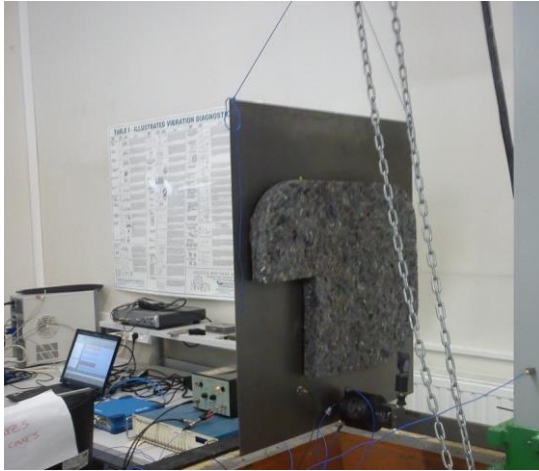
- Estimation of the noise $\bar{n}(t) = x(t) - \bar{s}(t)$

using the time synchronous averaging $\bar{s}(t)$
of the system response $x(t)$

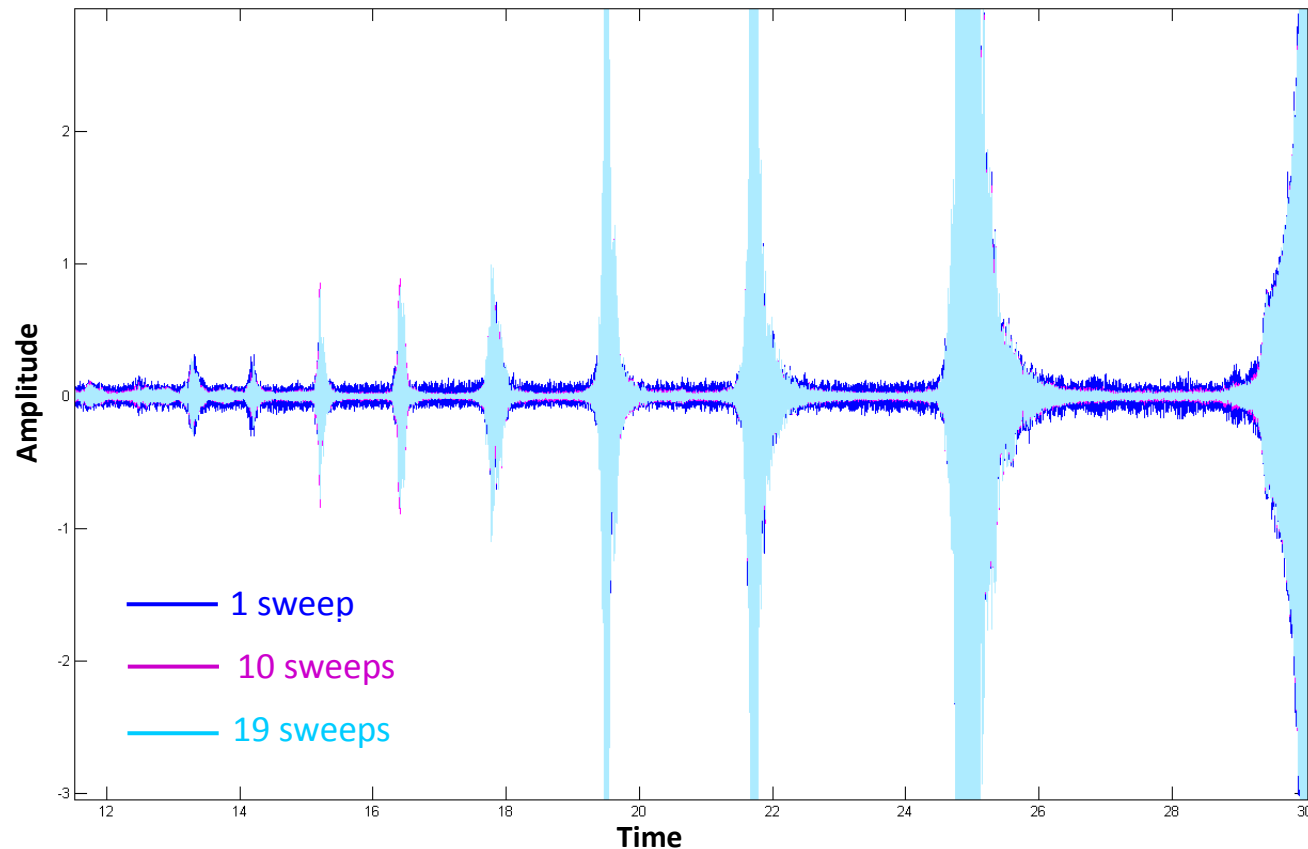
$$\bar{s}(t) = \frac{1}{K} \sum_{k=0}^{K-1} [x(t - kT)]$$

Application to a vibrating plate – Noise estimation

- Free-free damped steel plate (1mm)
- Shaker + Accelerometer



Influence of sweep repetitions (number of periods K)



Increase of K



Synchronous averaging
on **more periods**

$$\bar{s}(t) = \frac{1}{K} \sum_{k=0}^{K-1} [x(t - kT)]$$

→ Better extraction
of the noise

→ More precise estimations of
the kernels of high orders

Uncertainty of measurement using Bootstrap

How to study the
variability of the measurements ?



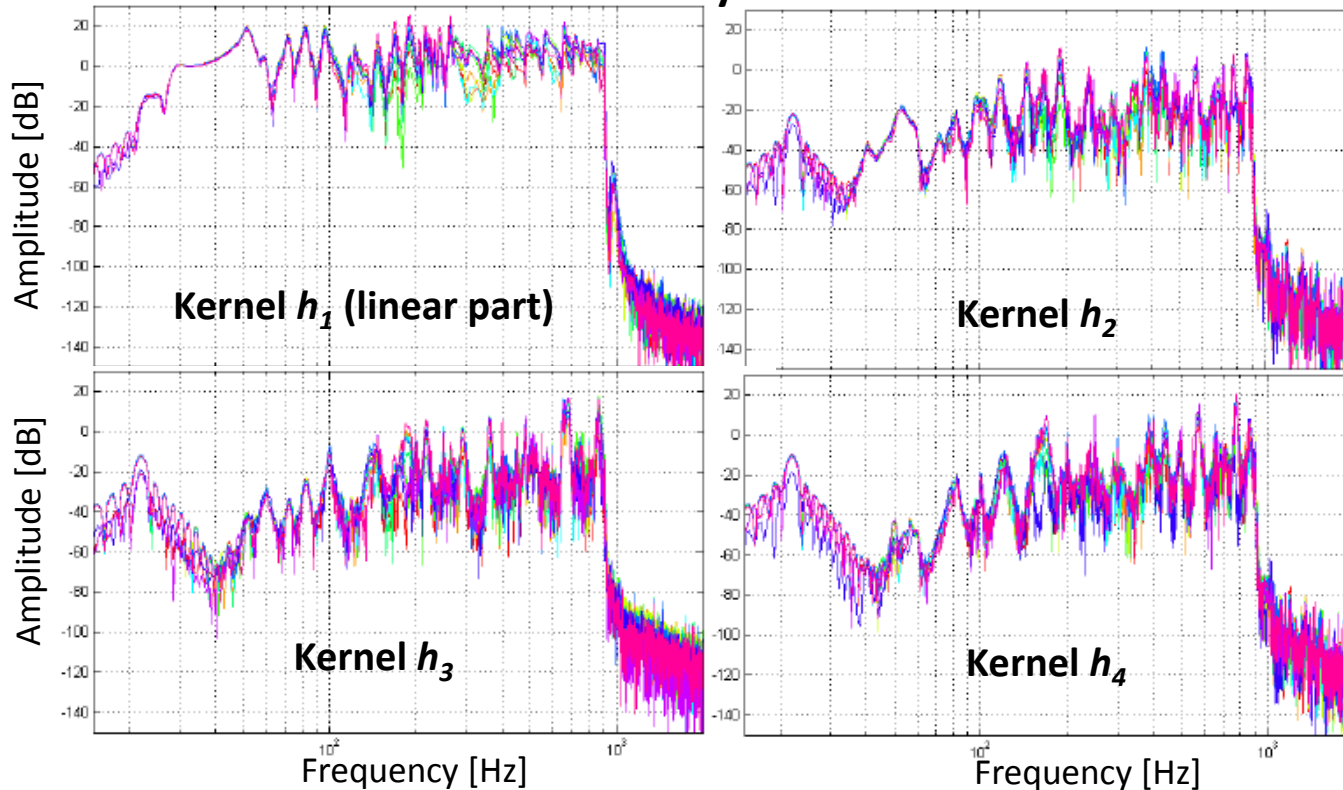
Bootstrap method

B random sample with replacement (of K sweeps each time)
Synchronous averaging on K repetitions



B different
kernel estimations

Identified Kernels of the system for $B=10$ and $K=19$



Way to identify and
quantify variability
(uncertainty) of plate
nonlinearities
estimations

Uncertainty of quantification

Synchronous averaging on K random draw with replacements (performed B times)

Estimation of parallel Hammertein model (performed B times)

Mean over the B estimations

K repetitions of exponential sine sweeps (ESS)

B estimations of the response

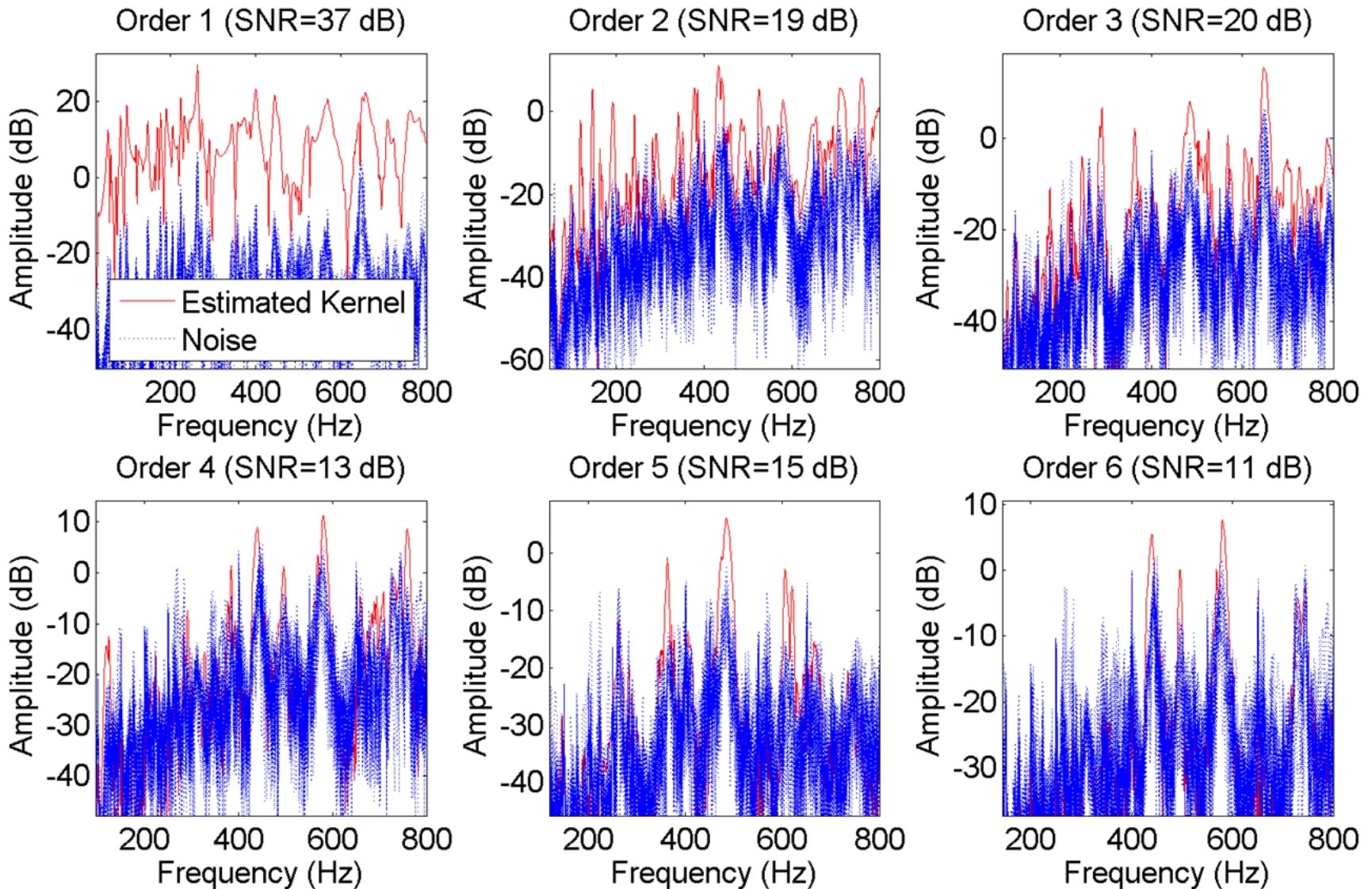
B estimations of the N kernels

1 mean estimation of the N Kernels

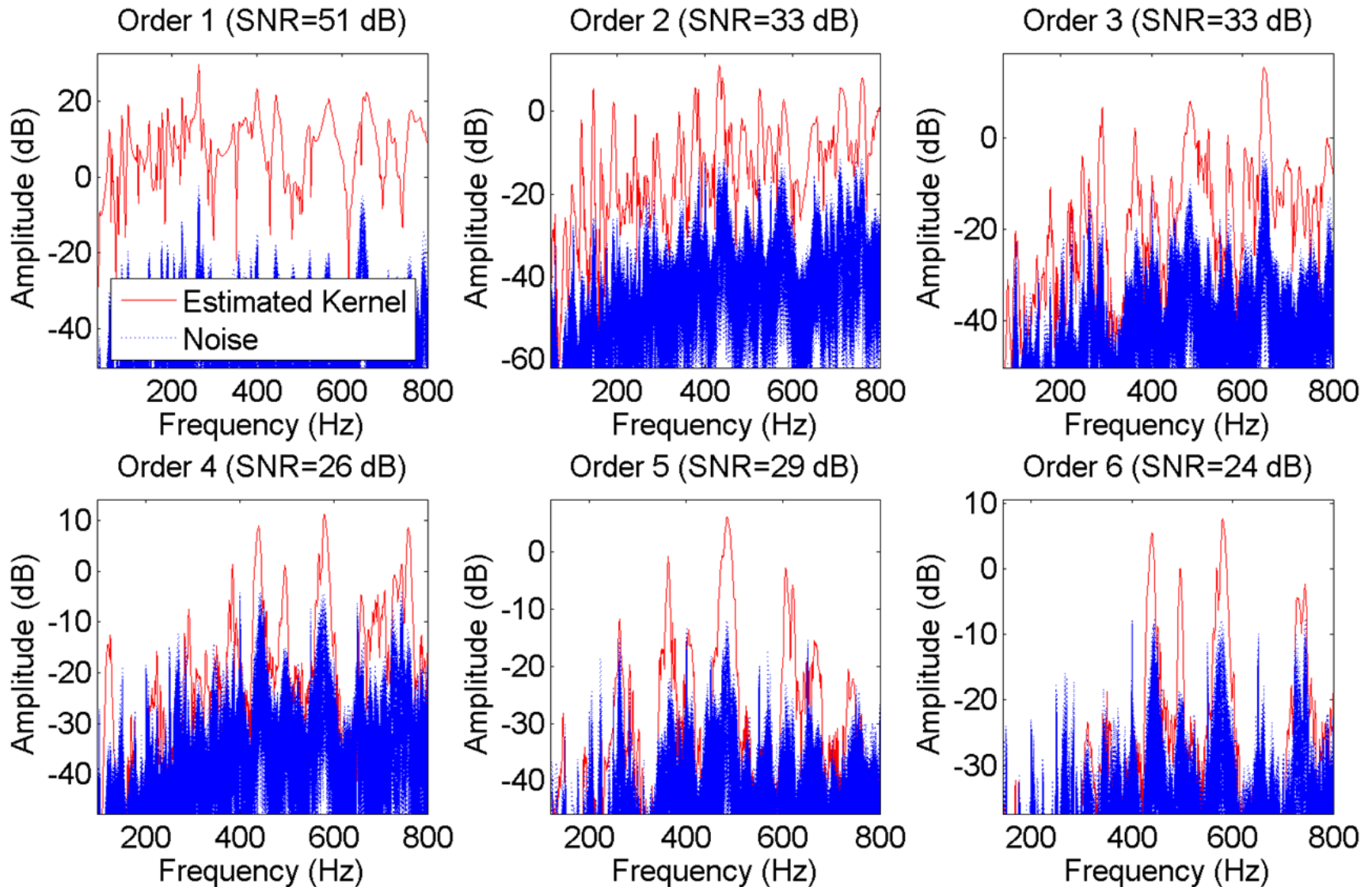


B estimations of the « estimation noise » on the N kernels

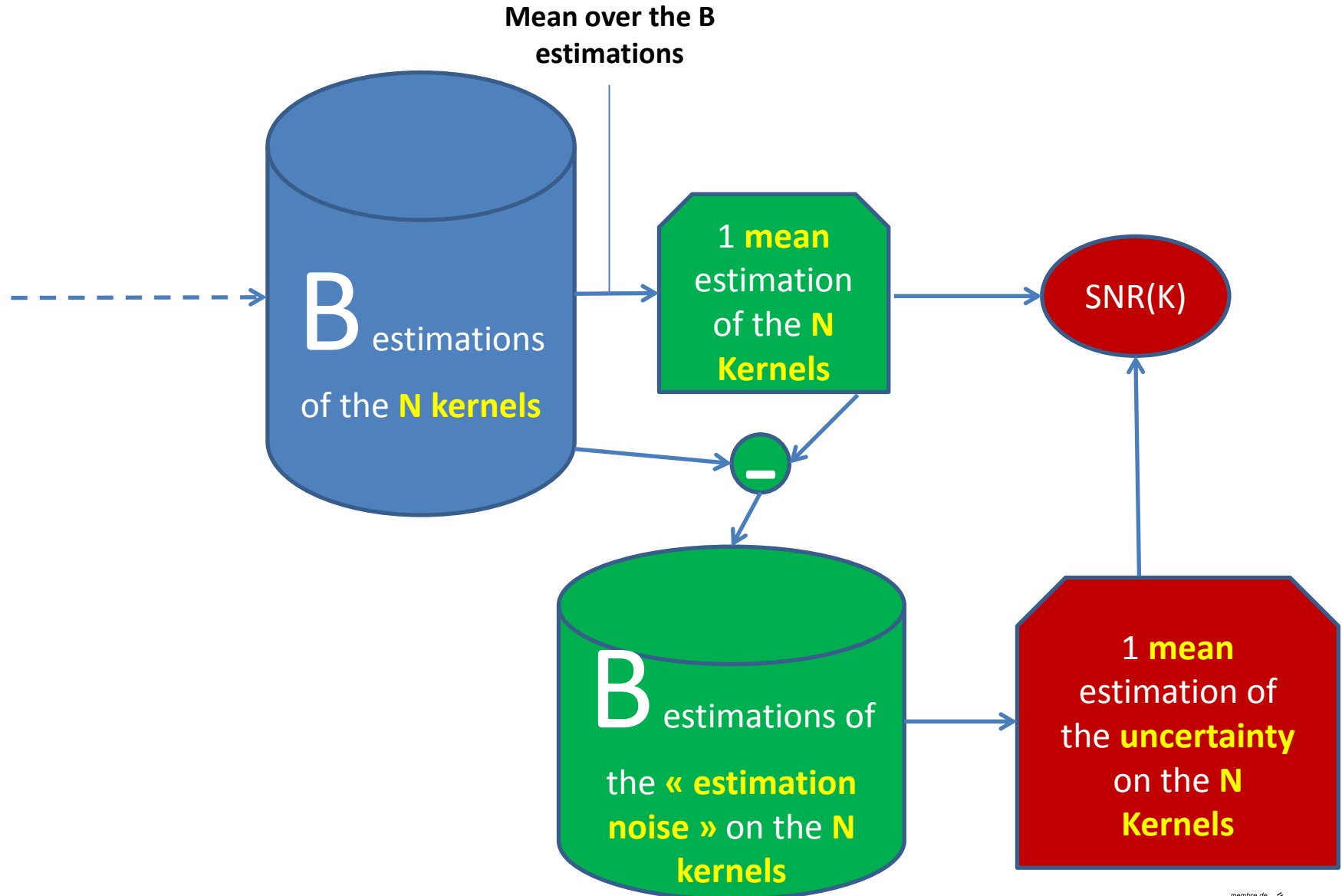
No averaging (K=1, B=150)



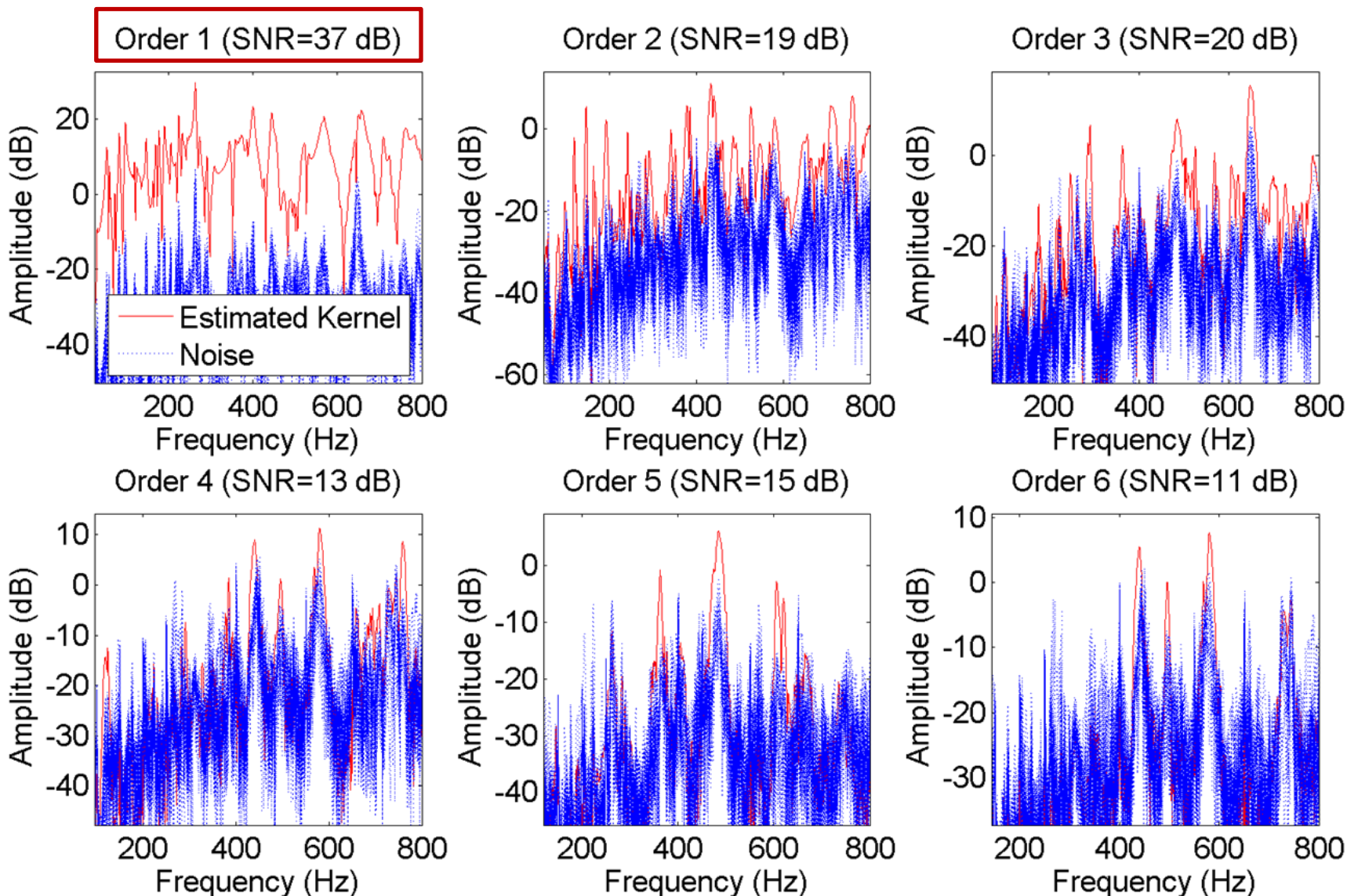
Averaging (K=19, B=150)



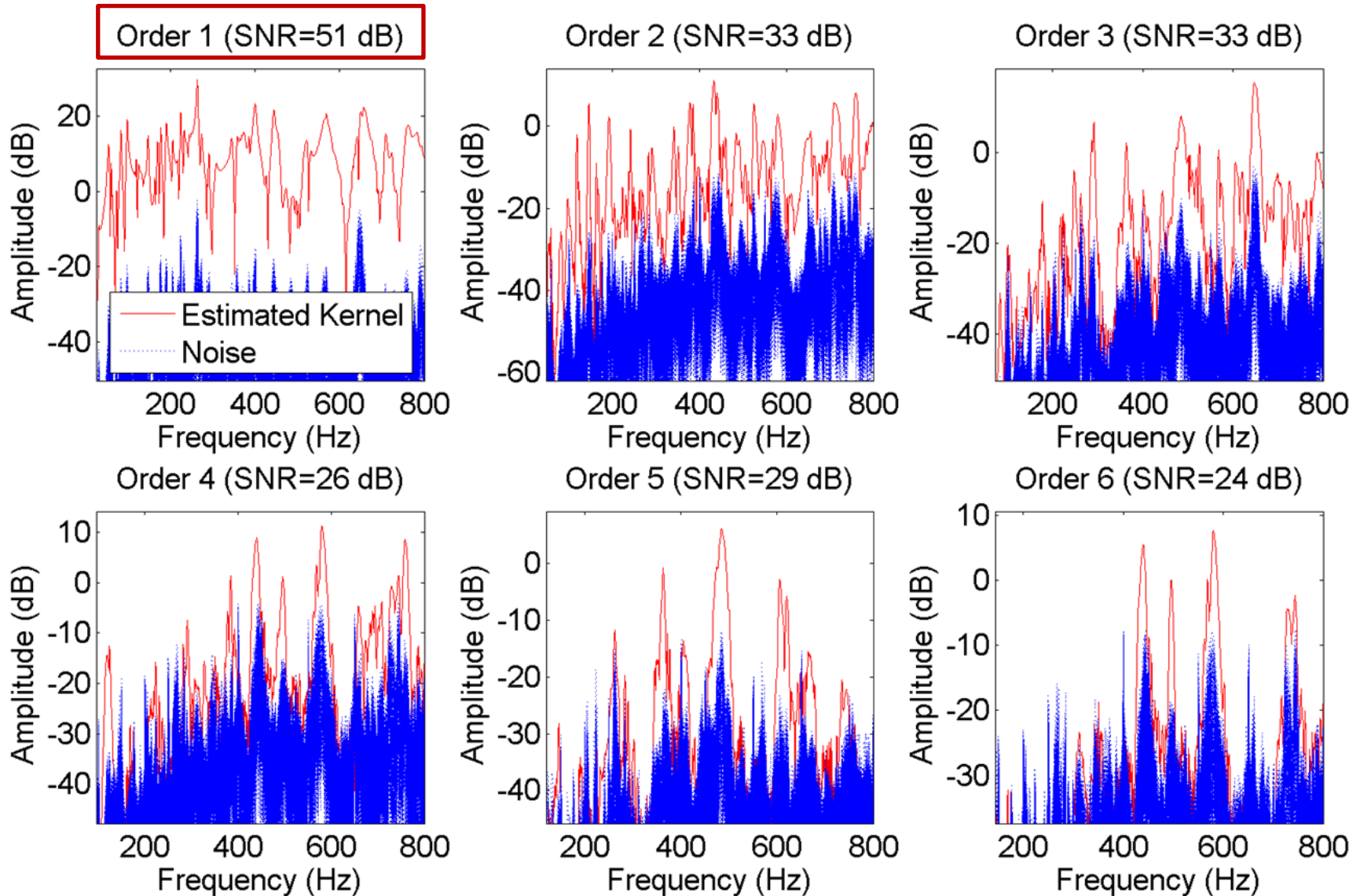
Uncertainty of quantification



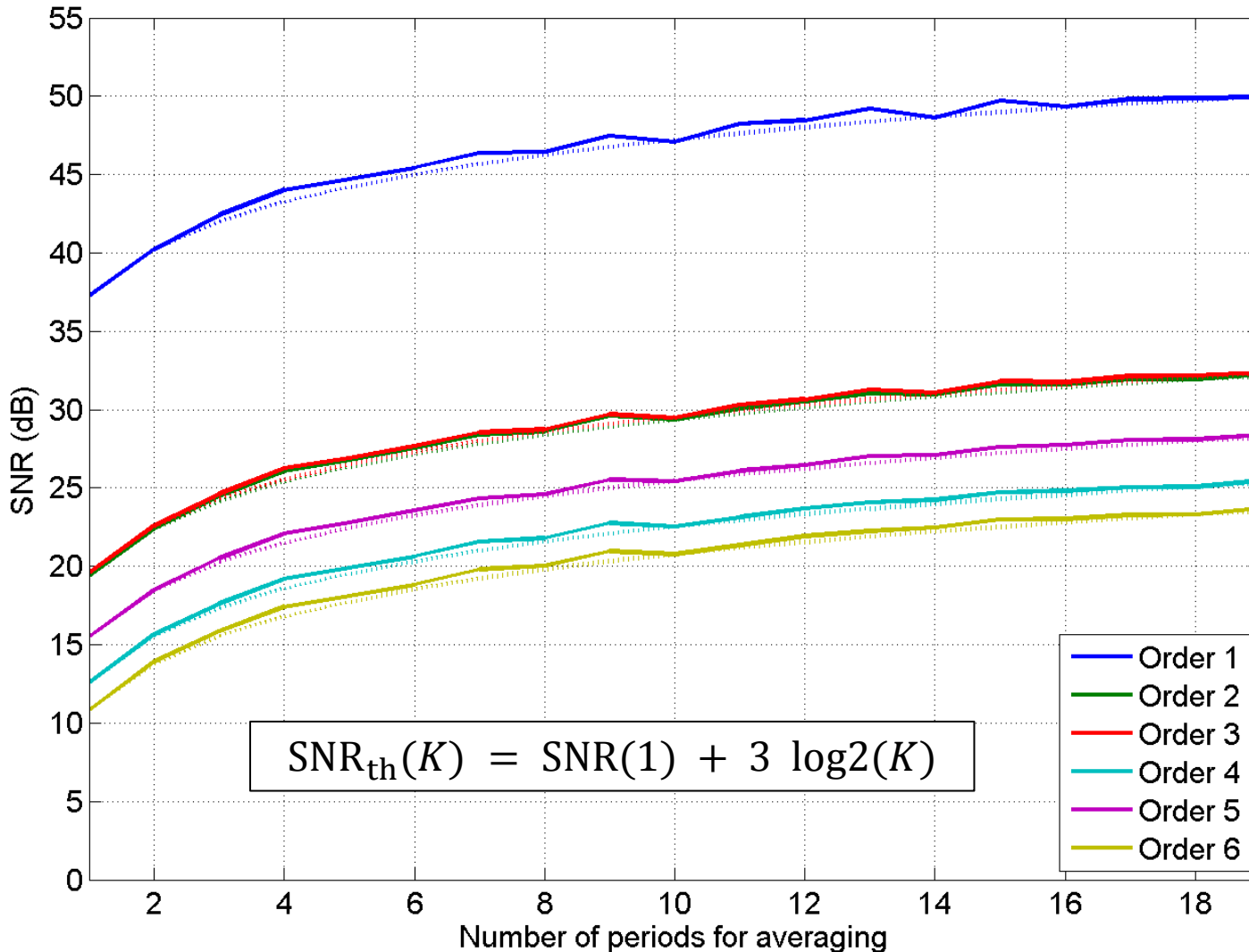
No averaging (K=1, B=150)



Averaging (K=19, B=150)

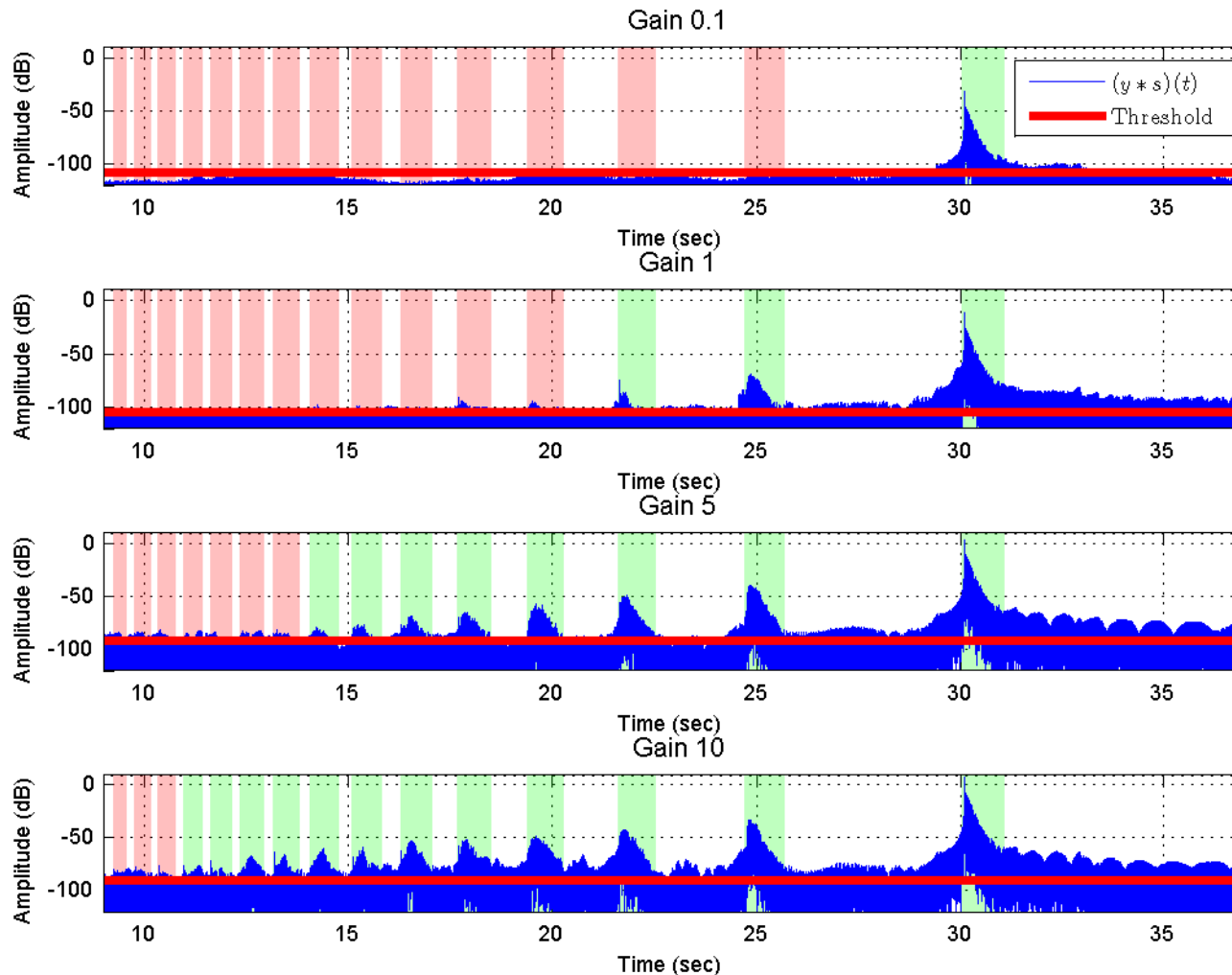


Effect of repetition number K on SNRs



Autonomous kernel order estimation

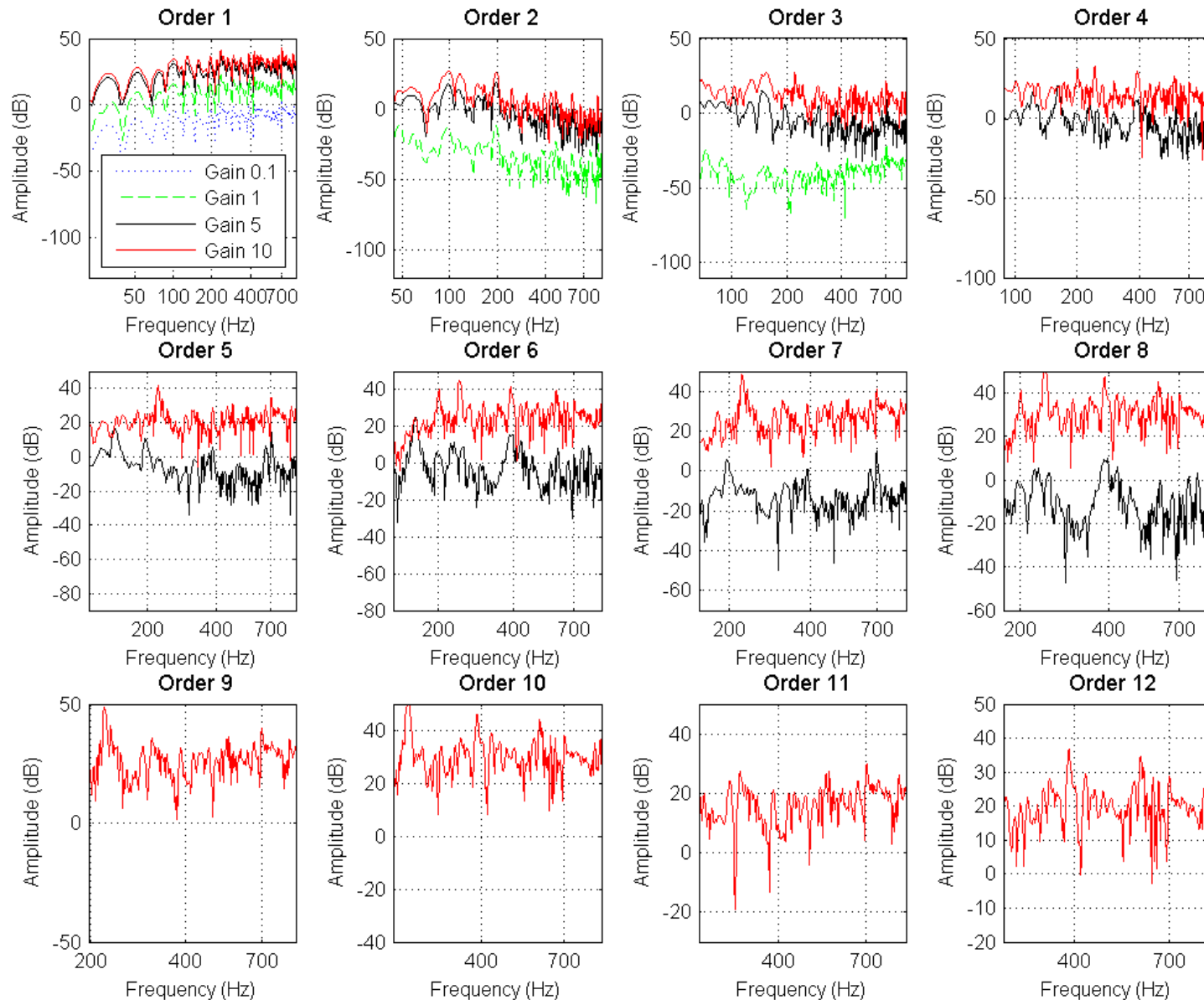
→ Example on the suspended damped plate (5 different gains)



Estimation of the proper kernel order N to identify

Threshold defined following a statistical F-test (Fisher)

Example of autonomous Kernel estimation



Conclusion & Perspectives

- Original method to **estimate the nonlinearities** of a vibro-acoustical structure
 - Slightly nonlinear systems modelled as **parallel Hammerstein models**
 - Kernels easily estimated using **exponential sine sweeps**
- **Improvements** of the sine sweep method
 - **Repetition of the excitation signal** – K sweeps
 - **Extraction of the noise** through time synchronous averaging
 - **Uncertainty estimation** by bootstrap
 - **Autonomous kernel order estimation**
- **Perspectives**
 - **Comparisons** with other methods (spectral domains): **periodic multisines...**